SOME STUDIES ON SMITH PREDICTOR BASED NETWORKED CONTROL SYSTEMS

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Some Studies On Smith Predictor Based Networked Control System

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by

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Dedicated

to

my loving parents and my younger brother Rizwan and my friends

Department of Electrical Engineering
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C E R T I F I C A T E

This is to certify that the thesis entitled ***"Some Studies On Smith Predictor Based Networked Control System"*** *by* ***Zeeshan Ahmad****, submitted to the National Institute of Technology, Rourkela for the award of Master of Technology in* ***Electrical Engineering*** *with specialization in* ***"Control & Automation"****, is a record of bona fide research work carried out by him in the* ***Department of Electrical Engineering****, under my supervision. I believe that this thesis fulfills part of the requirements for the award of degree of Master of Technology. The results embodied in the thesis have not been submitted for the award of any other degree elsewhere.*

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Contents

List of Abbreviations

Abbreviation	Description
NCS	Networked Control System
UDP	User Datagram Protocol
TCP	Transmission Control Protocol
CAN	Controller Area Networks
LAN	Local Area Networks
WAN	Wide Area Networks
PC	Personal Computer
RHS	Right Hand Side
IP	Internet Protocol
DAQ/DAS	Data Acquisition Syatem
NI	National Instruments
IP	Internet Protocol
ADC	Analog to Digital Converter
DAC	Digital to Analog Converter

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Abstract

An Networked Control System (NCS) uses real time communication network for closed loop control of systems. It is a class of distributed control system involving information sharing among sensors, actuators, controllers through a communication network.

The present work deals with the study and analysis of network delay, packet loss and their effects across the communication channel of an NCS. An User Datagram Protocol (UDP) has been used to establish the communication channel between the two computers in the real time, and hence the network delay and packet loss between them is studied. An UDP although unreliable due to non retransmission of the lost packets, is still preferred for control system applications because of the rate of data transmission in UDP is faster.

The adverse effect of network induced delay is reduced by using the classical Smith Predictor Compensator. Study on Smith Predictor performance along with a filter is made to reduce the disturbance introduced by the network. Further, the different combinations of the Smith Predictor, PI controller and Low Pass Filter (LPF) has been studied for its effect on the network delay and packet loss.

The experiment was performed on the developed networked DC Servo Motor control system and the designed P-I controller based on the relay Ziegler-Nicholas tuning for the speed control of the DC Servo Motor. The experimental results were in the good agreement with the simulation result.

Chapter 1

Introduction

1.1 Introduction to Networked Control System (NCS)

The definition of networked systems is that when two or more devices connected in such a way that they can share information is called network or we can say that they are connected through the network. There are two types of problem area encountered in networked system: first one is control of network and another one is control over network.Control of network means problem in network like routing control,congestion control. Control over network means control problem through data network i.e. networked control system. Now a days, control community is aimed to increase research as integration of control, computer network, communication and computer science.

Feedback control system where in the control loop closed by the real-time network is called Networked Control System [1]. The physical plant, sensor, controller, actuator are difficult to be located at the same place, and thus signals are required to be transmitted from one place to other. In modern industrial systems, these components are often connected over network media giving rise to the so-called NCS.

In basic NCS the physical plant, controller, sensor and actuator are not located at the same place in industry so that information is required to transmit from one location to other location. The information send through the network media or we can say that real-time network so that closed loop is completely connected. Block diagram represent the basic networked control system. In which the physical plant, sensor and actuator are located at the same place and controller is located at another place. Network connection is required between these two places so that they can share information.

A NCS is a control system in which the control loops are closed through the real time network is called NCS. The defining feature of NCS is that information package(feedback signal or control signal)is exchanged among the system component through the network.

In NCS data transfer from sensor to controller and control signal from controller to actuator through the network. In NCS data are communicate in the form of packets through the network. PID control is widely used in network control system because it gives better performance.

NCSs are one type of distributed control system where sensor, actuator, plant and controller are connected through the communication network. The research area of NCS is an inter-disciplinary which is combining both communication and control. A major work in modern industry is to integrate control, communication and computing into different level of machine operation. The traditional control system architecture is point-to-point in which each sensor and actuator is connected through the a separate wire to control and plant. If we use common bus then this is introduce delay in the network or we can say that introduce the delay between sensor to controller and controller to actuator. NCS research area are mostly focus on two area:communication protocol and control design.

In NCS used communication network in the feedback path of the closed loop control system which makes the design of NCS is difficult and analysis is also complex. Conventional control theory has many ideal assumptions like no delay between sensor to control and control to actuator, synchronized control these assumptions reevaluate before apply to the NCS. Another issue for NCS is network-induced delay, network- induced delay occur when data transfer through network from one device to another device. Packet loss occur when data is transmit through the unreliable network or we can that unreliable transmission path. Packet transmission through unreliable network causes delay and in worse case it causes packet loss in the transmission.

In NCS two area of research.They are control of network and control over network. Control of network deals with the problems in communication network i.e routing control, congestion control. Control over network deals with the control problem through data network, this type of system is called NCS [2].

Now a days, data networking technology has been widely used in the control of industries and military applications. These application mainly manufacturing of plant, aircraft and automobile. Network is used to connect these control application components like sensor, actuator and controller effectively reduce the cost of the overall NCS. These application components connects through the network so they remotely control the plant. Network used in these applications are specific such as CAN(Controller Area Networks) and LAN(Local Area Networks).

1.2 Background

In NCS, Network is used to transmit data from one place to another. Data is transmitted in the form of binary. There are several technique to transmit data from one place to another place. These binary massage are arranged in the form of packets with formatting and address information along with data. These packets or frames are in the form, in which they have header(also called preamble), data(called payload) and trailer. The header contains error checking and addressing information, data contains the actual information which we want to transmit and trailer contains error checking and massage management information(like stop bit and parity bit).

Simplex transmission is only one direction transmission, Half duplex is one way transmission at a time either it receives the data or send the data and full duplex is two way transmission at a time it means receive or send same time. In addition to this, synchronous and asynchronous transmission are also present. Synchronous(clocked) transmission are timed in which both devices know exactly when will transmission start and end. In Asynchronous(unclocked) transmission there is marking for start and end of transmission, so that synchronous transmission is faster than asynchronous transmission.

1.2.1 Network and Control

NCS combine two engineering fields control and computer network. Network is used to transmit data from one place to another, it can be wired or wireless. NCS is implemented over a network so that good understanding of communication network protocol is required to analyze the behavior of NCS. In a NCS feedback loop is closed through the real-time network. Defining feature of an NCS is that control and feedback signal or packets exchange through the network. Two types of network used in NCS, they are classified as dedicated and non-dedicated. A dedicated network is known as control network and non-dedicated network is known as data network. Some of the current control networks used for design NCS are Ethernet, Device Net and Control Net [3].

The main aim of the control design for NCS is to stabilize the system, improve system performance and meet control system specification. These specification includes transient response, peak time, overshoot, phase margin and gain margin. Network used in NCS introduce the delay in the system, so controller design in such a way so that system meet system specification and stabilize the system. If system could not meet system specification then design a controller such a way that compensate the delay and makes the system stable.

1.2.2 Point-to-Point Architecture of NCS

In point-to-point architecture of NCS each sensors and actuators are connected through the separate wire to the plant and to the controller. Fig 1.1 shows point-to-point architecture of NCS and it is a traditional model of Networked Control System. It is shown in the figure that such system increases the complexity, number of connected devices, wiring, volume and weight of the point-to-point NCS.

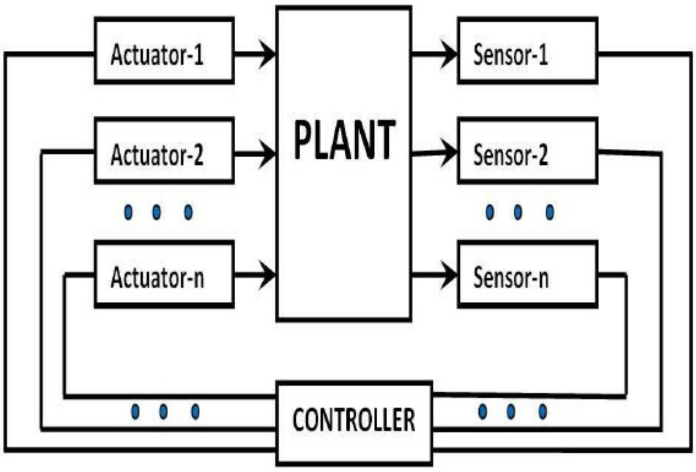

Figure 1.1: Point-to-Point Architecture of NCS

1.2.3 Basic NCS

A networked control system is a close loop control system where the feedback loops are closed by communication network [4]. An NCS benefits its implementer by reduced wiring ,system maintenance, and reduced cost. Fig 1.2 shows the typical block diagram of NCS. NCS are not have same design assumptions as non network discrete-time and continues-time system like no data loss, no delay or fix delay and fixed transmission rate.

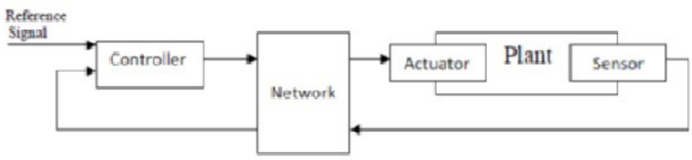

Figure 1.2: A Block Diagram of Networked Control System

A General NCS structure is shown in fig 1.3.NCS is real-time distributed control system, which consist controller, plant, sensor, and actuator. These device are connected through the electronic network, which is used to communicate between these devices. The controller should be time driven or event driven, so it can calculate the new so it can calculate the new control signal at discrete time instants with a constant sample time or it can calculate the control signal immediately once it gets a new measurement from the sensor. In addition, the actuator can be time or event-driven. These devices

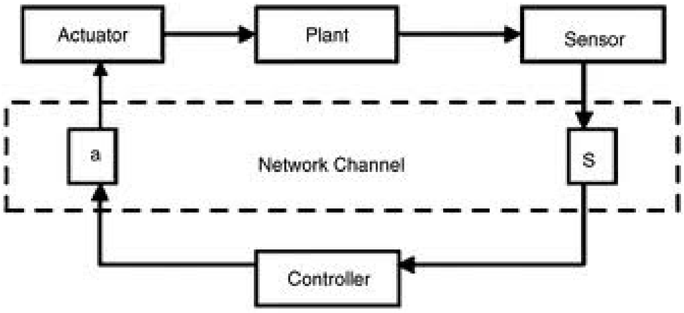

Figure 1.3: Network Control System set-up

are difficult to locate at one place so that as shown in fig 1.3 controller is physically placed different location from the sensor, plant and actuator.

1.3 Fundamental issues in NCS

In this section we analyze the problem associated with the NCS. NCS issues involve various delays present in NCS and packet dropouts in a network. In an NCS, various delays with variable length occur due to sharing a common network medium [5]. Problems associated with the NCS are two, first one is network induced delay and another one is packet loss, both problems have been discussed below-

1.3.1 Network induced delay in NCS

In an NCS, most significant feature is network-induced delay, which naturally brings negative effect on NCS stability and performance. This effects on NCS gives importance to the study of time-delay systems. Network induced delay occur when network is induced in the NCS. It occur when plant, control, sensor and actuator exchange information through the network [6]. To transmit a continuous time signal over a network, the signal must be sampled, encoded in a digital format, transmitted over the network, and finally the data must be decoded at the receiver side. This process is significantly different from the usual periodic sampling in digital control. The overall delay between sampling and eventual decoding at the receiver can be highly variable because both the network access delays (i.e., the time it takes for a shared network to accept data) and the transmission delays (i.e., the time during which data are in transit inside the network [7]

1.3.2 Packet Loss in NCS

Packet loss occur rarely in NCS when node failure and massage collision occur in the network. In most network protocol re-transmission occur when packet lost, but it is for limited time period after the time period expire new data send by the sender. In some network protocol re-transmission not occur, once packet is lost than it is not not recover but it is good for real-time feedback control system.Controller every time receive new data for control signal generation [5]. Feedback control system can accept certain amount of packet loss after that system performance degrade and destabilize the system. System is stable only when packet transmission occur at certain rate and to calculate the lower bound of packet transmission rate.

1.4 Applications of NCS

- It is easy to add more sensors, actuators and controllers with very little cost and without heavy structural changes to the whole system. Potential applications of NCS [8].
- Manufacture automation factories
- Electric factories
- Advanced aircraft
- Energy management Systems (EMS) for generation control and network analysis
- Mobile sensor networks
- Remote surgery

- Haptics collaboration over the internet
- Automated highway systems and unmanned aerial vehicles
- NCS utilizing high-performance workstations with server/client technologies are used widely for stable and efficient power system operation

1.5 Literature Survey

Networked Control System(NCS) is a growing topic for research interest in multidisciplinary engineering. NCS research mainly include network used and design of a controller for delay compensation and stabilization. Instide of above, NCS co design is also topic of interest for many researchers [9, 10]. A close loop system with real time network in feedback loop form a NCS [11] [12] [7] [13]. Networks are the main part of NCS, there are many literature on network used in NCS [3]. Now these days wireless network is used in NCS [14]. Insertion of this network introduce delay in the system .A delay degrade the performance and destabilize [12] of a system.Apart from delay there are other issue like jitter [5] and packet loss are also present. Communicate the two PC with the help of UDP protocol.These two PCs are connected through the LAN so that it introduce the packet loss and delay.

Now the system stability is the main issue for control design and analysis. Two approach for control design direct and indirect. Direct assume no delay and indirect assume delay in the system. So that we used P-I controller design for speed control of DC servo motor.DC servo motor model taken from [15].The main aim of P-I controller design is fine tuning of parameter gains. The tuning method for PID controller was introduced by Ziegler-Nicholas in 1942.They proposed a tuning method as step responce and sustain oscillation method [16] [17]. It is not good for higher order system [18].So that advanced tuning method like analytic, predictor [19] and auto tuning [20] developed.Manually tuning is very complex so that relay auto tuning is introduced by Astrom and Huggland.

Now Network is used in the system so that it introduce the delay. O. J. Smith developed a control structure in 1950 to compensate the time delay. Normey-Rico and Camacho [21] proposed the filtered Smith predictor(FSP), used to control the stable, integrating and unstable time delay process. Analysis and Design of this type of compensator is used for only constant delays, generalized for time varying delay. In our example, we consider the stable plant which is DC servo motor model. P-I controller is designed by Ziegler-nicols tuning consider derivative term is zero. Delay is taken as the average delay between two PC communication. Now we design a discrete Low Pass Filter(LPF) to see the effect on delay.It is designed by the window technique.

1.6 Problem Formulation

The main objectives of thesis are

1. Develop a real-time networked control system through the Communication between two PC using UDP in Simulink.
2. PI-Controller design for DC Servo motor and speed control of DC Servo motor experimental setup.
3. Design Smith Predictor Controller for compensate the time delay induced by the communication network and tuning of predictor filter.

1.7 Contribution of Thesis

The main contribution of the thesis are

1. Study the Networked Control System(NCS) and its different aspect.
2. Modelling of DC Servo motor and experiment on DC Servo motor setup for speed control with the design of P-I controller.
3. Stability analysis of networked stable plant with smith predictor time delay compensation and tuning of predictor filter.
4. Two PC communication through the network with the help of User Datagram Protocol(UDP).

5. Discrete filter design by window technique and see the effect on delay.

1.8 Thesis Organization

The Thesis is organized as below-

- In chapter-2, Real time Communication between two PC with the help of UDP and study the delay characteristics and packet loss.
- In chapter-3, DC Servo Motor overview, modelling ,speed control and P-I control design.
- In chapter-4, Smith predictor design to compensate the time-delay and predictor filter tuning.
- In chapter-5, Discrete Low Pass Filter Design to see the effect on delay and Design of networked smith predictor.
- In chapter-6, Conclude the thesis and future work discussed

Chapter 2

Real-Time Communication Between Two Personal Computers Using UDP

2.1 Introduction

In this chapter, we communicate the two PC with the help of simulink and UDP protocol. Two computers are connected through the LAN. Firstly install the setup of real time karnel in both the PC so that real time communication takes place. After that makes the simulink model for both the PC to communicate, In open one PC is sender and another PC is used as receiver but in close loop communication both PCs are used as a sender as well as receiver. Hence we can say open loop is one way communication and close loop is two way communication. Data is send through the network in the form of packets from one PC to other PC. In case of node failure, traffic and congestion these packets have been lost or we can say that data loss.There is delay also occur due to network, it is network-delay.After that plot the network-delay characteristics and pack-loss characteristics.

2.2 UDP COMMUNICATION

Internet Protocol(IP) Suite have the set of network protocols used for the Internet, in which the User Datagram Protocol(UDP) is the core member.On an IP network two PCs are connected then they can communicate through

UDP, computer application send information in the form of datagrams from one PC to other PC. UDP has no handshaking signals hence it is unreliable communication. UDP use minimum protocol hence it is a simple transmission model. UDP is unreliable communication so that it has no guarantee for delivery, duplicate protection and ordering.UDP send the data in the form of datagram as a packet. UDP has no guarantee to the upper layer protocol for message delivery. UDP use check sum method for error checking. It has no retransmission hence it is used in real time application. UDP use IP address and port number for communication between source and destination.

2.2.1 UDP Packets

UDP sends information in the form of UDP packets or datagrams.Packets has two parts as shown in fig 2.1, first one is header and another one is data. Header size is fix of 8 bytes and data is varying from 0 to 65527.

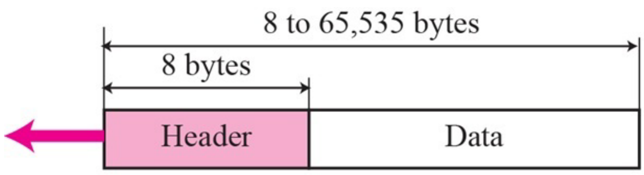

Figure 2.1: UDP User Datagram

Now we discuss UDP header as shown in fig 2.2, it consist of four parts.First part is source port number, it has source port address if necessary otherwise it would be zero. Second part is destination port address, it has remote port address and it must be specified because it is required to transmit data. Third part is length,it is specified the total length data plus header. Fourth part is checksum, it is check the error in data and header, it is not necessary if not specified then field uses all value zero.

0	16 31
Source port number	Destination port number
Total length	Checksum

Figure 2.2: UDP Header Format

2.3 Set-up for UDP communication between two personal computers using Matlab

Here we used two computers to communicate, these are local PC and Remote PC,

2.3.1 Steps for local computer

- Install the real-time kernel in Matlab, command used to install is "rtwintgt -install" , as shown in fig 2.3.

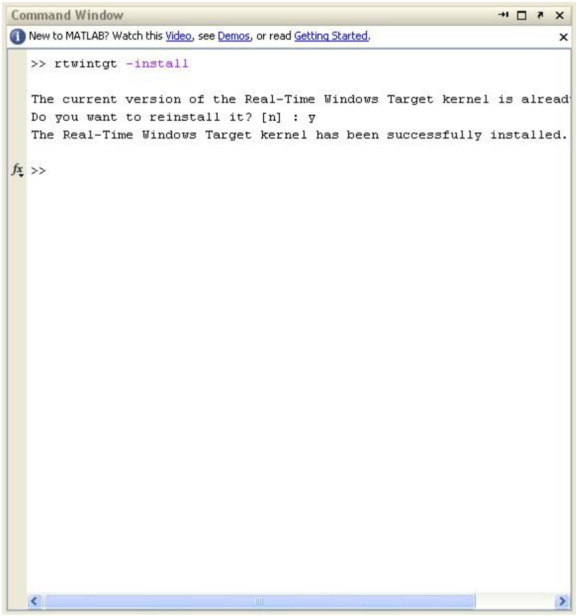

Figure 2.3: Matlab Command Window for install real-time kernel

- Make new model.
- Add a Pack block from simulink library

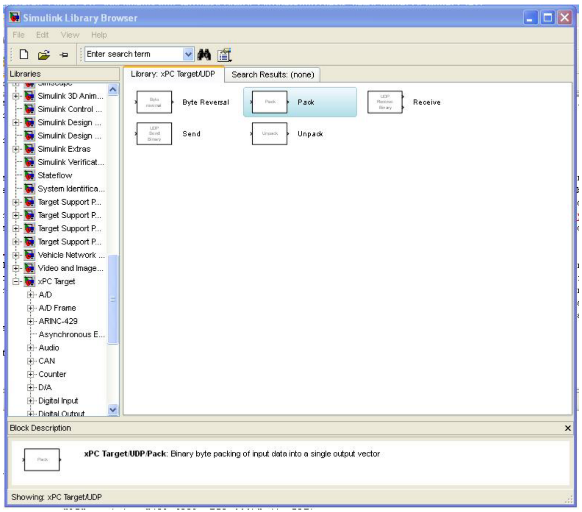

Figure 2.4: Simulink library window

- Add a UDP send block from simulink library as shown in fig 2.4.
- Add a Signal generator from simulink library.
- Set Pack block parameter as shown in fig 2.5.

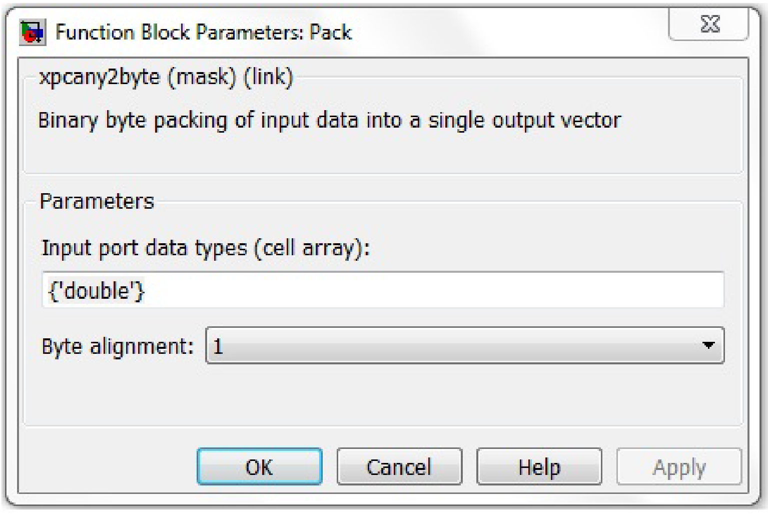

Figure 2.5: Pack block parameter

- Set UDP send block parameter as shown in fig 2.6.

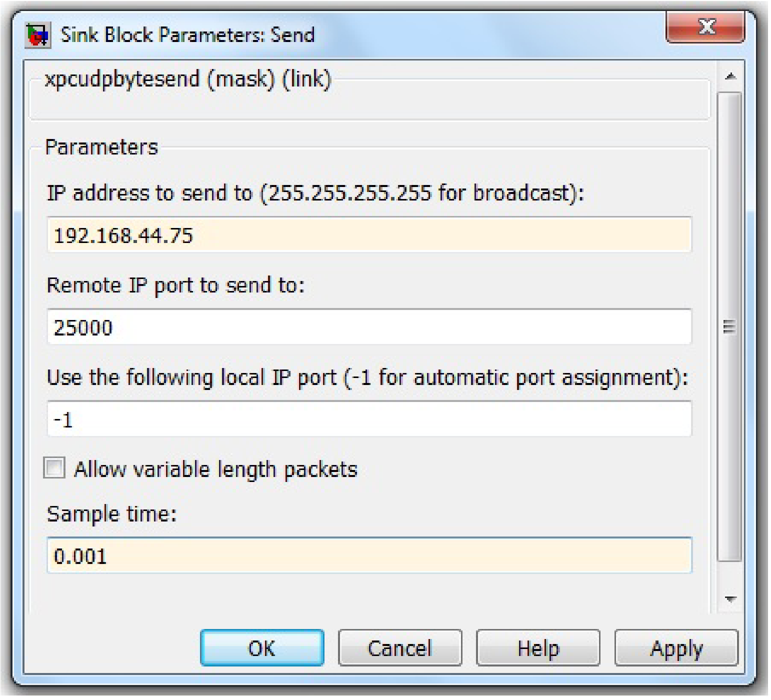

Figure 2.6: UDP send block parameter

2.3.2 Steps for Remote computer

- First step is same as local PC
- Make new model.
- Add a Unpack block from simulink library
- Add a UDP receive block from simulink library.
- Add a Scope from simulink library.
- Set Unpack block parameter as shown in fig 2.7.

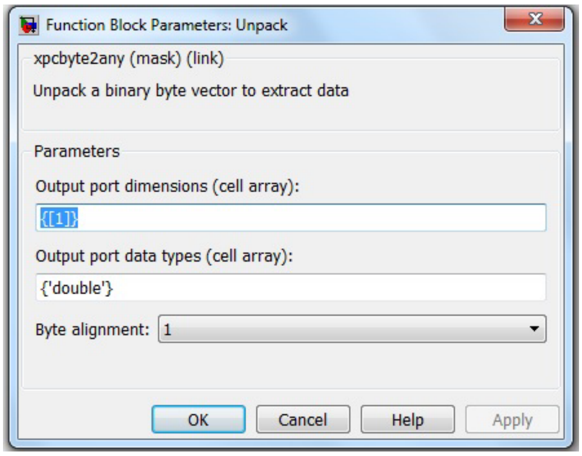

Figure 2.7: Unpack block parameter

- Set UDP receive block parameter as shown in fig 2.8.

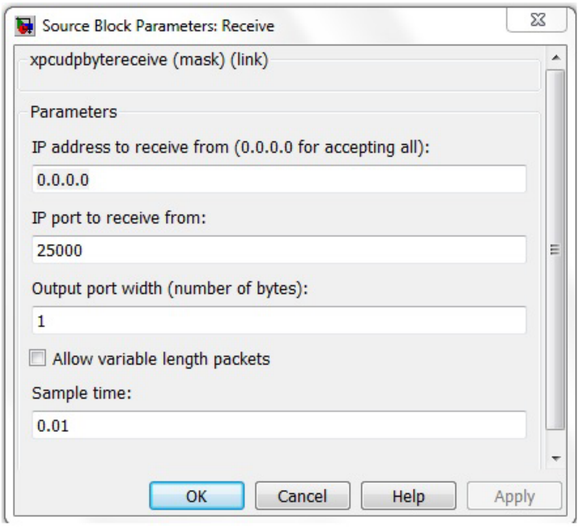

Figure 2.8: UDP send block parameter

These are steps for setup a simulink model in local as well as remote PC, to communicate.

2.4 Open loop and close loop communication through UDP

There are two types of communication between two PC open loop and closed loop. In open one PC is only send and another PC is only receive the signal.In closed loop communication both PC send or receive the signal so that they can be used as controller and plant.Controller and plant form a close if they communicate in both ways hence it is called as a close loop communication.

2.4.1 Open Loop Communication

In open loop communization, send a signal to another computer from one computer or we can say that send signal from one computer and receive by another computer.In another word local computer to remote computer signal transmission where local computer send signal and remote computer receive signal, so that it is also called local PC to remote PC communication.Matlab simulink diagram for remote and local PC as shown below-

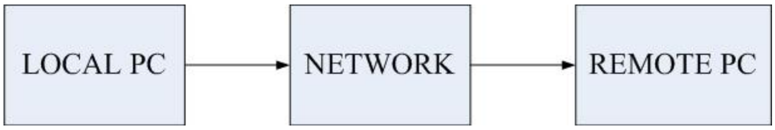

Figure 2.9: Open Loop Block Diagram

In the above shown diagram we see that local computer transmit the signal and remote computer receive the signal. Simulink diagram for that is given below -

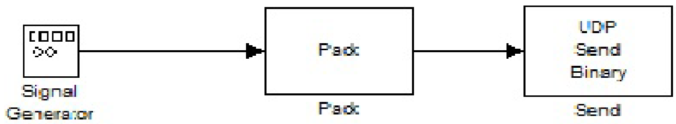

Figure 2.10: Simulink Block Diagram for Local PC

In the above shown diagram one diagram is for local PC and another one is for remote PC. Local PC simulink diagram three blocks are there first one is source block which is used to generate the signal then it goes to UDP Pack block which is used to convert one or more signal of varying data types into one single 'uint8' data type which is required by the UDP send block. UDP Pack block parameters are input port data type and byte alignment. Input port data-types specify the data types for the different signals as part of the block parameters. The supported data types are double, single, int8, uint8, int16, uint16, int32, uint32, and Boolean. The block determines the sizes of the signals automatically. The byte alignment field specifies how the data types are aligned. The possible values are: 1, 2, 4, and 8. The byte alignment scheme is simple, and ensures that each element in the list of signals starts on a boundary specified by the alignment relative to the start of the vector.If field specifies for example 1 and total incoming signals are three then first signal start at byte 0, second start at byte 1, third start at byte 2 and again first signal and so on.UDP send block has only one input port which receive the signal in 'uint8' format and send it as a UDP packet. In its block parameter properties IP address and IP port are specify of remote PC.Use local IP port and sample time default value -1.

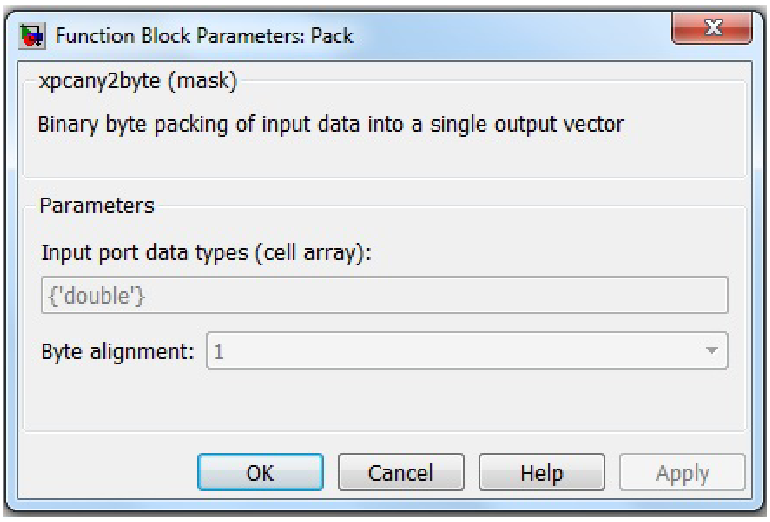

Figure 2.11: Pack Block Parameter

In remote PC, data has been process as shown in figure and its simulink diagram three blocks are present.The three blocks are UDP receive, Unpack and scope.firstly UDP receive the data in UDP packet format and it has two output port. first port gives the output as a receive data in 'uint8' format, second port used as a flag indication if it is 1 then new data is receive otherwise no new data has been received.

Now this is the figure for signal which is send by the local PC and signal which is receive by the remote PC.

In this figure, see that sine wave has been transfer as a data signal by the local PC, in the form of UDP packet converted by UDP pack block.These

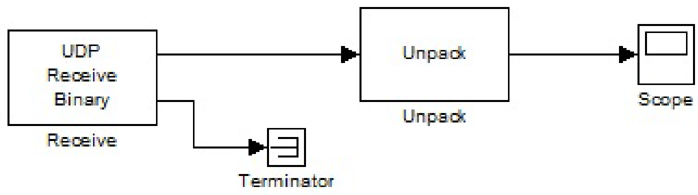

Figure 2.12: Simulink Block Diagram for Remote PC

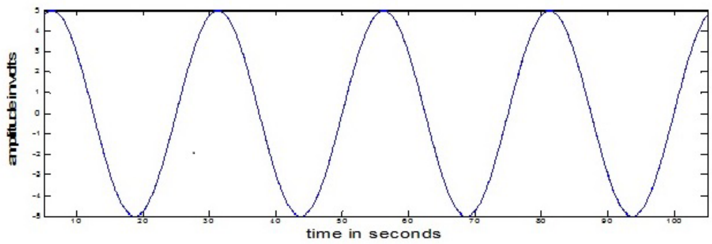

Figure 2.13: Send Signal

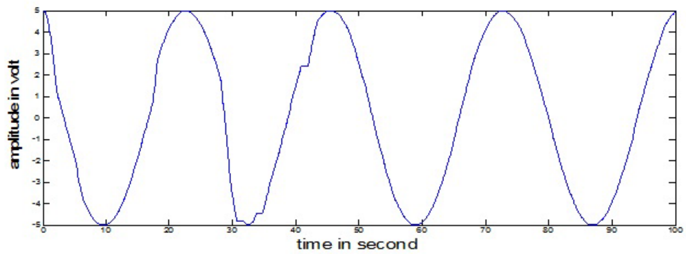

Figure 2.14: Receive Signal

packets have been received by the remote PC, UDP unpack block convert these packets into analog signal which is also a sine wave as seen in the scope as well as in the figure. The received signal by the remote PC is not ideally match the send signal, there are some loss of information as shown in figure. This is called a open loop communication because one PC is only send the signal and other PC only receive the signal.

2.4.2 Closed Loop Communication

In closed loop communication, sends the data signal from local computer to remote computer and remote computer send this received signal to the local computer. In local computer compares the original send signal and received signal, after comparison calculate the delay and packet loss in the received signal.We communicate the two computers through the UDP (User Datagram Protocol), which is unreliable way to communicate so that there is loss of information in the received signal. Block diagram represent a way to communicate two computers in a close loop-

Figure 2.15: closed loop communication

In block diagram of closed loop communication as shown in fig 2.15, see that there is a local computer and another one remote computer. They are connected through the network as shown in figure. Network used in our communication system is Local Area Network(LAN). Close loop communication takes place through the UDP. There are simulink diagram for local computer as well as remote computer so that communication takes place.

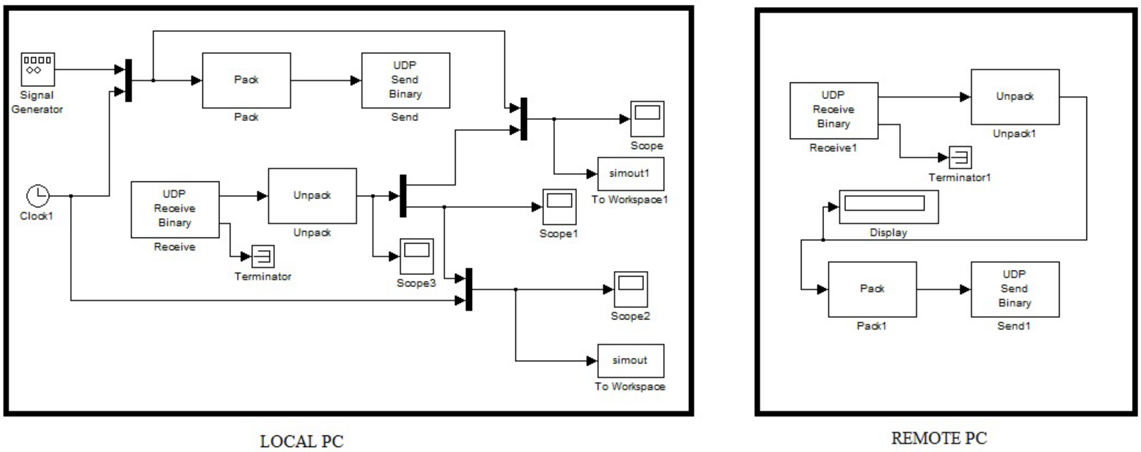

Figure 2.16: Close Loop Communication Model

In close loop communication simulink diagram there some blocks are same as present in the open loop simulink model except clock block. Clock block is used to generates a time signal.The Clock block outputs the current simulation time at each simulation step. This block is useful for other blocks that need the simulation time. In remote PC simulink block there is one more extra block other than open loop i.e. terminate block which is used to terminate the not connect output of the block. If do not connect these output it gives warning. It is called as a close loop communication because if local PC is used as controller and remote PC is used as a plant then they send information to each other so that it is form a close loop control system hence it is called as a close loop communication.

2.5 Network delay and packet loss characteristics

In close loop communication signal is send from local PC to remote PC and this signal again send back to local PC.Clock is also send for the simulation time and for calculating the average delay and packet loss. We compare the send clock value to the receive clock value at each sampling time for fix time period this gives us delay value for each sampling time and also find the average value of delay for fix interval.

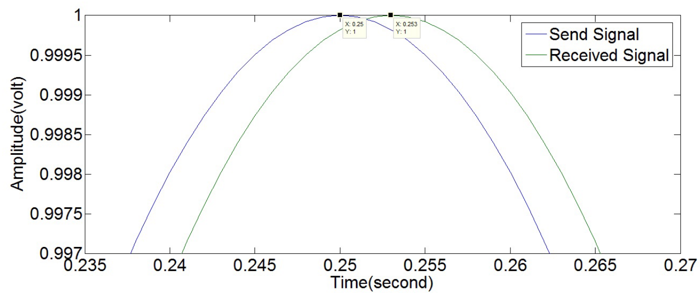

Figure 2.17: Delay with sampling period 1ms

As we see in the fig 2.17, that the delay is 1ms and blue line shown in the figure is send signal and another one is received or delayed signal. The send data is not perfectly received at the receiver side hence we can that there is loss in the information. In UDP transmission, data are transmit in

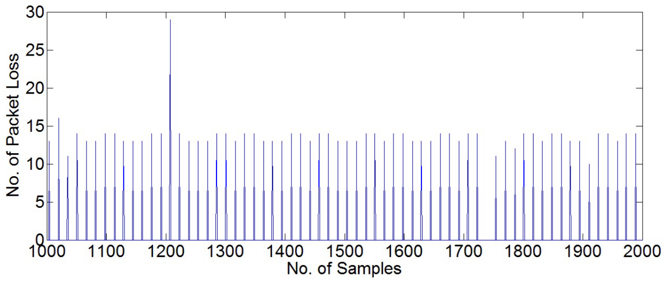

Figure 2.18: Packet loss with sampling period 1ms

the form of packets and it is unreliable. So that there are packet loss in the communication. As shown in fig2.18 no. of packet loss in between samples. For calculating the packet loss we compare the clock signal value to next clock signal value at every sampling interval if they are same then there is a packet loss in the information.

2.6 Chapter Summary

Real-time Communication between two PC has been done using UDP.UDP is better to use in real-time communication because it cannot waste time to retransmit. It is transmitted new updated data every time so that controller generates updated control input. Delay has been occur due to network i.e. network delay. Network-delay increases sampling time increases as shown in result and also packet loss.

Chapter 3

Computer Based D.C.Motor Modeling and Speed Control

3.1 Introduction

DC Motor control has been used for variable speed and position applications for many decades and historically were the first choices for speed control applications requiring accurate speed control, controllable torque, reliability and simplicity. The basic principle of a DC variable speed drive is that the speed of a separately excited DC motor is directly proportional to the voltage applied to the armature of the DC motor.

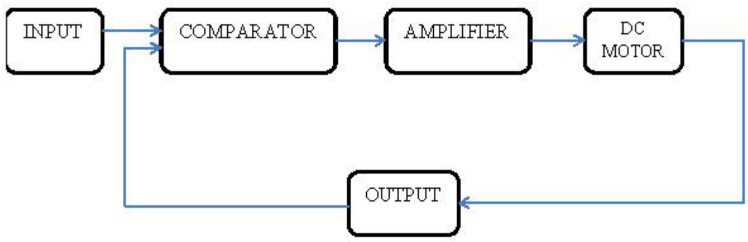

Figure 3.1: Block Diagram For DC Servo Control System

DC motor servo speed block diagram shown in above fig3.1. Input signal is give as a desired signal and output signal received as a actual signal.Comparator block is compare the desired signal to the actuator signal and gives the error signal.This error signal then amplify by the amplifier to drive the DC motor.The DC motor is connected to a gear system that drives the output shaft such that its position can be modified.

3.2 D.C. Motor modeling

The Mathematical Model of DC Motor explained in this section,which gives the transfer function of the DC Motor. The External DC voltage is given in the armature of the DC Motor that develop the motor torque, which produce result as motor speed. The applied DC voltage produced the armature current and in the permanent magnetic field it produce current and motion [15]. The DC Motor is basically a transducer which converts the electrical energy into mechanical energy. The armature current and field flux produces a torque on the motor shaft.

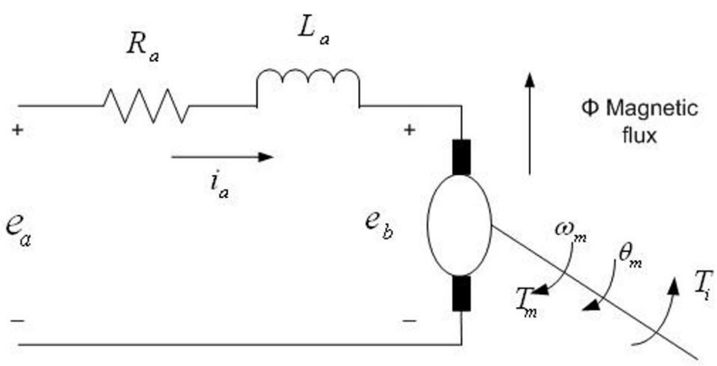

Figure 3.2: A schematic diagram of DC motor

The DC motor is used widely in control system application so that it is necessary to develop a mathematical model of the DC motor.A schematic diagram of DC motor as shown in the figure. Torque developed by the motor(T_m)is proportional to the magnetic flux ϕ and armature currenti_a.

$$T_m(t) = k_m(t)\phi i_a(t) \tag{3.1}$$

As the flux constant above equation(2.1) can be written as

$$T_m(t) = k_i i_a(t) \tag{3.2}$$

R_a	Armature Resistance(ohms)
L_a	Armature Inductance(H)
$i_a(t)$	Armature Current(Ampere)
$e_a(t)$	Applied Armature voltage(volt)
$e_b(t)$	Back emf (volt)
$T_m(t)$	Torque Develop by motor(Nm)
θ_m	Angular Displacement of Motor Shaft(rad)
j_m	Moment of Inertia of Motor Shaft(kg-m^2)
B_m	Viscus Friction of Motor Shaft(Nm/rad/s)
ϕ	Magnetic Flux
i(t)	Field Current(Ampere)

Table 3.1: Symbol Used for DC Motor

The motor back emf is proportional to speed of the motor

$$e_b(t) = k_b \frac{\theta_m}{dt} \tag{3.3}$$

where k_i is motor torque constant and k_b is the back emf constant, apply the KVL in the shown loop we can get the following equation

$$L_a \frac{di_a}{dt} + R_a i_a(t) + e_b(t) = e_a(t) \tag{3.4}$$

Develop Torque equation using the above equation

$$j_m \frac{d^2\theta_m}{dt^2} + B_m \frac{\theta_m}{dt} = T_m \tag{3.5}$$

Taking the Laplace Transform of above equations,we can get

$$E_b(s) = K_i s \theta_m(s) \tag{3.6}$$

$$(L_a(s) + R_a)I_a(s) = E_a(s) - E_b(s) \tag{3.7}$$

$$(J_m s^2 + B_m s)\theta_m(s) = K_i I_a(s) \tag{3.8}$$

substitute the value of equation (3.6) and (3.7) into the equation(3.8), we can get the transfer function(where input voltage and output speed)of DC motor

$$\frac{\dot{\theta_m}(s)}{E_a(s)} = \frac{K_i}{(J_m s + B_m)(L_a s + R_a) + K_i K_b} \tag{3.9}$$

In SI unit K_i and K_b are equal then we use K_i=K_b=K so transfer function becomes

$$\frac{\dot{\theta_m}(s)}{E_a(s)} = \frac{K}{(J_m s + B_m)(L_a s + R_a) + K^2} \tag{3.10}$$

In the above transfer function speed is the output but we can get position also as the output so that the transfer function becomes

$$\frac{\theta_m(s)}{E_a(s)} = \frac{K}{s((J_m s + B_m)(L_a s + R_a) + K^2)} \tag{3.11}$$

$$\frac{\theta_m(s)}{E_a(s)} = \frac{K}{s(J_m L_a s^2 + B_m L_a s + J_m R_a s + B_m R_a + K^2)} \tag{3.12}$$

Now the model of DC Servo motor has been taken from the system identification toolbox in Matlab Simulink-

$$\frac{\dot{\theta_m}(s)}{E_a(s)} = \frac{71050}{5.18s^2 + 8180s + 10200} \tag{3.13}$$

3.3 PI Controller Design

Proportional Integral Controller is good for increase the speed of the response and also eliminate the steady state error of the response.P-I Controller is having two terms combination Proportional and Integral term. P-I Controller developed because of the desirable property that system is having type-1 transfer function for open loop and it is having zero steady state error for unit step input. In P-I Controller design use Ziegler-Nicholas PID tuning method, in which Derivative term is zero. In Ziegler-Nicholas closed loop tuning method only proportional term is used and all other terms are treated as zero. In this method controller gain increased until the output of the process is having sustain oscillation, as shown in the fig3.4.

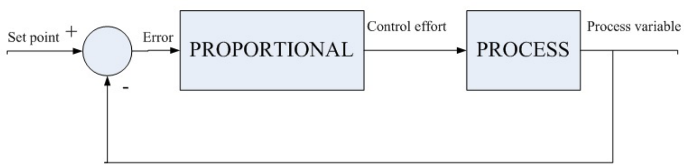

Figure 3.3: Ziegler-Nicholas closed loop test

From the above shown fig3.5 we can find out the value of T_u, which is period of process output i.e. having sustain oscillation as shown in the above fig3.4. P_u is called the ultimate gain and its value is equal to the smallest

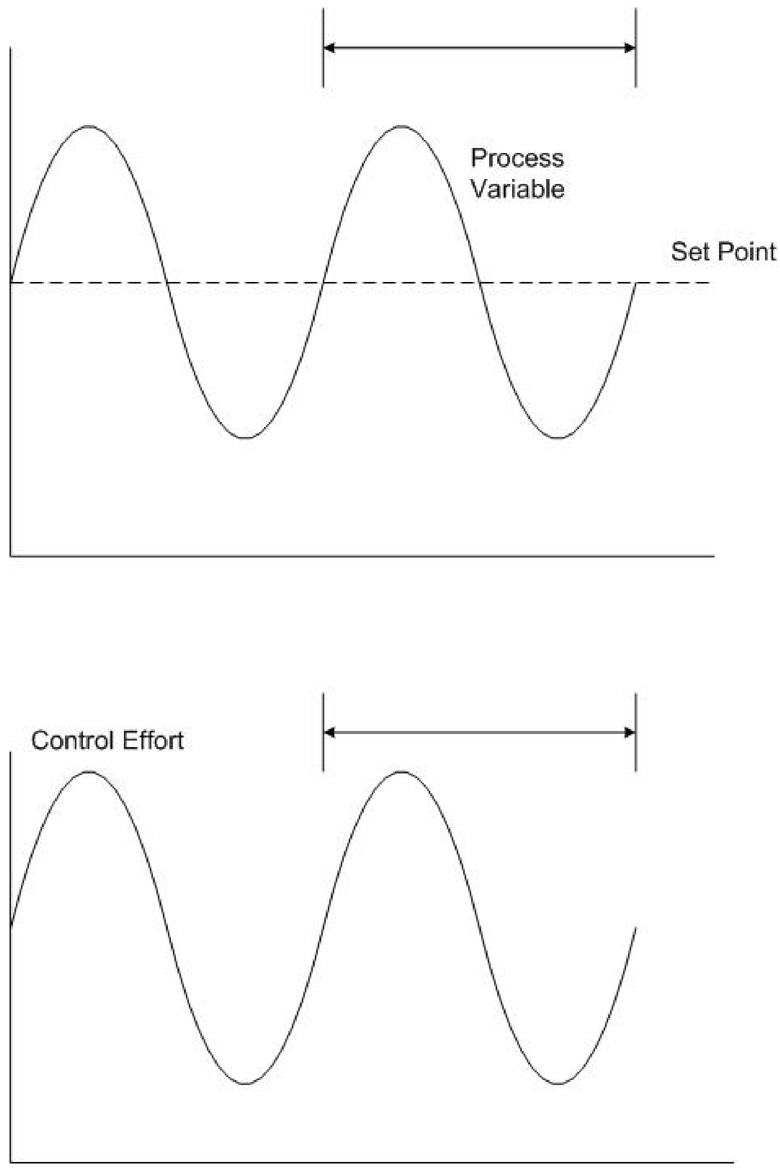

Figure 3.4: Control effect and process variable signal

proportional gain value that can cause sustain oscillation in the output of the process. After the computation of these values, we can find out the tuning parameter by Ziegler-Nicholas tuning rule-

P=0.6P_u

T_i=0.5T_u

After finding P and T_i, we need to find the controller transfer function

$$G_c(s) = P * (1 + \frac{1}{T_i s}) \tag{3.14}$$

Forcing the closed loop system into sustained oscillations with a proportional controller reveals the process's ultimate gain P_u and ultimate period T_u. Unfortunately, doing so can also cause dramatic and sometimes dangerous swings in the control effort and the process variable. So that relay method generates a sustained oscillation of the process variable but with the amplitude of those oscillations restricted to a safe range.

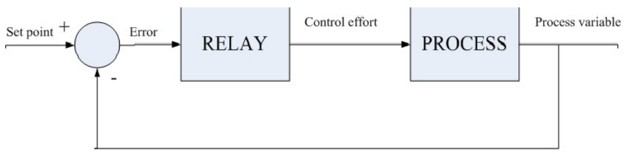

Figure 3.5: relay test

In the relay test proportional controller is disabled and on/off relay is used as shown in fig3.5 to apply a step-like control effort to the process. Then it hold control effect value constant and wait for process variable for greater than set point. At that point it apply a negative step and wait the process variable to below the set point. This process is repeated every time process variable passes the set point in either direction forces the process variable to oscillate at the same frequency of the control effect signal [22].

To identify the ultimate period T_u and ultimate gain P_u of the process, the control engineer running the test temporarily disables the Proportional block and replaces it with an on/off relay that forces the process variable to oscillate. The engineer then measures T_u directly from the square-wave control effort and computes the value of P_u according to P_u = (4b) / (Πa)

After find the value of T_u and P_u put these values in Ziegler-Nicholas closed loop test formulas and find values of P and T_i. These values put in PI controller transfer function as below so that PI controller value find which gives satisfactory result.

$$G_c(s) = \frac{0.1s + 13.88}{s} \tag{3.15}$$

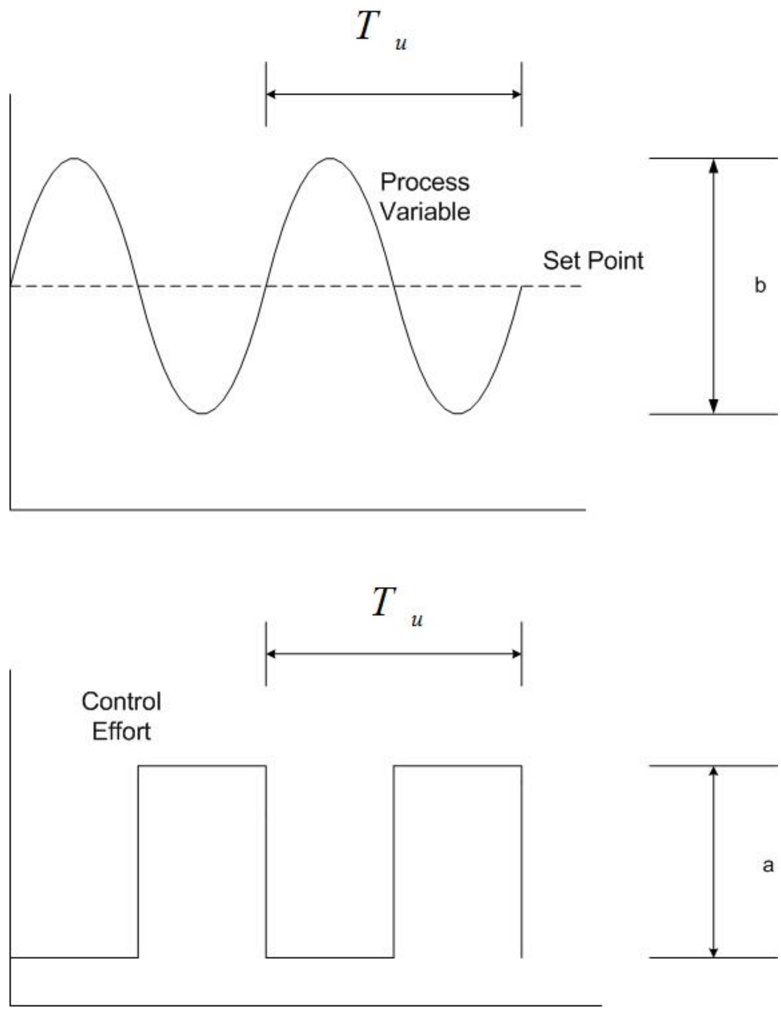

Figure 3.6: Control effect and process variable signal

3.4 D.C. Motor Speed Control Control Result

In the DC Servo motor speed result fig3.7, see that experimental result and result with P-I controller tract each other hence we can say that speed of the DC servo motor has been control. As shown in fig3.7, the experimental result is square wave because input is square and simulate result in which we apply P-I controller track the after settling which is very less. Here P-I controller is used so that steady state error is zero as shown in fig3.7 and also gives faster response. Initial response of the experimental setup does not match due to slow pick up of techo-generator.

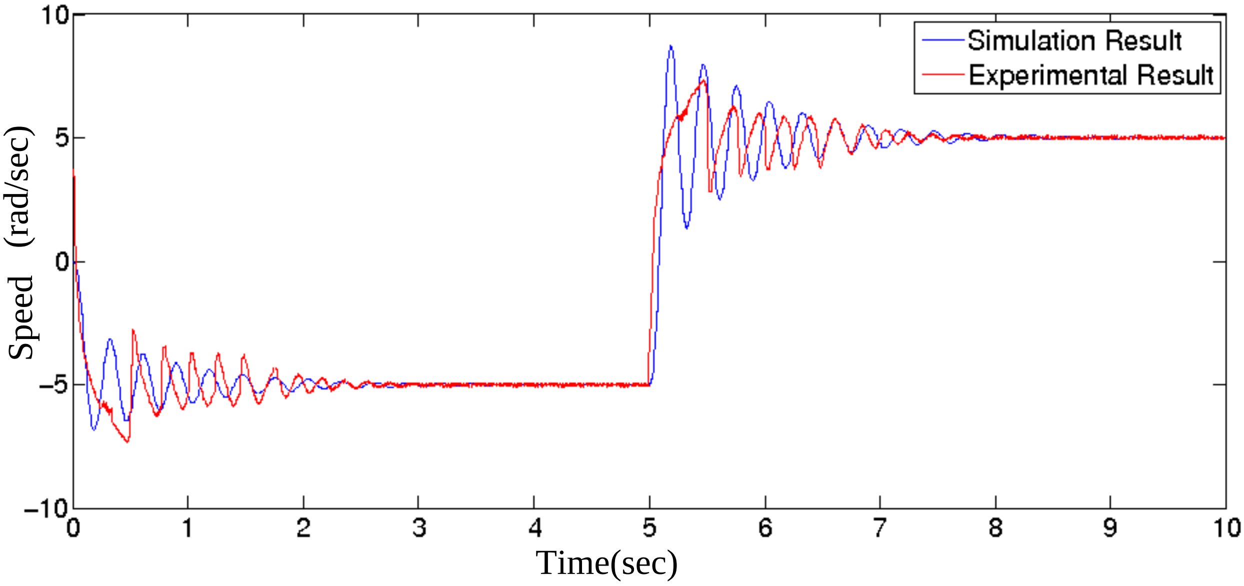

Figure 3.7: DC Motor Speed Comparison

3.5 Chapter Summary

In this chapter first things we have done is modelling of DC Servo motor. After that design a P-I controller for speed control of DC Servo motor. P-I controller gives good result. Compare the simulated result using P-I controller to the experimental result and they track each other hence P-I controller control the speed of the DC Servo motor.

Chapter 4

Stability Analysis of Filtered Smith Predictor(FSP) for Time Delay Process

4.1 Introduction

In many industries dead time are mainly due to the time required by process [23]. Traditional Controllers are difficult to use in process with time-delay because of the negative phase introduce by the dead time [24]. This is overcome by the using of dead time compensator so that it improve the performance of the closed loop system. Smith Predictor is the first dead time compensator algorithm and its main aim to compensate the delay from the characteristic equation [25]. Smith Predictor is used in stable process and cannot used to improve the disturbance rejection response [24]. To improve the disturbance rejection response several authors have proposed modified version of Smith Predictor. Normey-Rico and Camacho [21] proposed the filtered Smith predictor (FSP), used to control the stable, integrating and unstable time delay process. Analysis and Design of this type of compensator is used for only constant delays.

In some cases, the closed loop system is having a time-varying delay like network based controller. So that Control problem becomes difficult and analysis is also difficult in time varying delay, where delay is also large. These condition motivate the study of time varying discrete time system.Different control technique analyze to solve this problem such as static feedback law, dynamic controller and predictor based control. Here in this chapter improvement obtain for constant delay case can be extended to time varying delay case. Normey-Rico and Camacho [21] present unified approach for constant delay case is generalized for time varying delay case.

In our case we used network based filtered Smith Predictor(FSP) to compensate the time varying delay. Networked based controller or we can say that networked based filtered smith predictor(FSP) controller is placed at one place and plant is at another place and controlled by FSP controller. These two are connected by a network so that it is called networked filtered smith predictor(FSP).

4.2 Filtered Smith Predictor

In this section we briefly discussed the FSP. The structure of discrete filtered smith predictor is shown in figure where P(z) is plant model(stable, integrating or unstable), $P_n(z)$ is the nominal model of the plant which is equal to $G_n(z)z^{-d_n}$, $G_n(z)$ is the nominal delay free model of the plant, d_n is the nominal discrete dead time, $F_r(z)$ is the predictor filter and $G_c(z)$ is the primary controller.Discrete signals shown in figure they all are function of variable k, where r(k) is the reference signal, y(k) is the sampled output ,$\hat{y}(k)$ is the model output, $e_p(k)$ is the prediction error and $y_p(k)$ is the output prediction d_n instant of time ahead plus the filter prediction error.

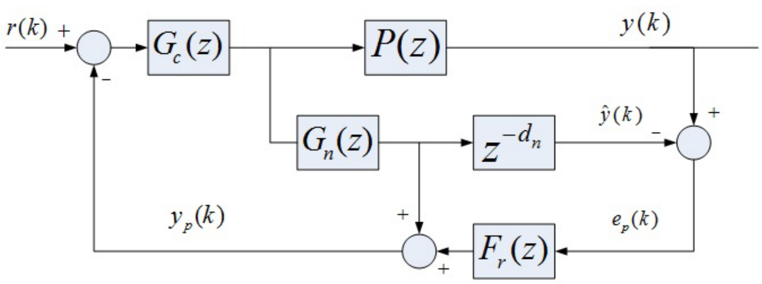

Figure 4.1: Discrete Filtered Smith Predictor

For stable implementation of Filtered Smith Predictor(FSP) for any process model is shown fig4.2. This scheme is used for implementation of FSP, where S(z) is stable and S(z)=$G_n(z)[1 - z^{-d_n}F_r(z)]$. Predictor filter plays important role like reject disturbance, attenuate noise and guarantee the internal stability of control structure.

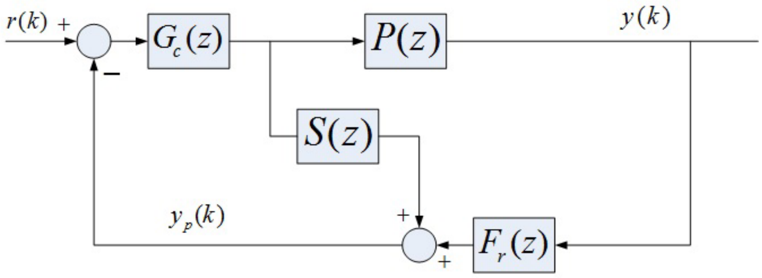

Figure 4.2: Implementation of FSP

4.3 Tuning of Filtered Smith Predictor

There are two steps to tune the FSP. First step is to design the primary controller by Ziegler-Nicholas method for the dead time free nominal model of the plant$G_n(z)$. Second step is to $F_r(z)$ tuned to obtain a stable S(z). Now we Consider the nominal model of plant $G_n(z)$ represented in terms of equation shown below, it has numerator and denominator terms as in equation, where it has undesired poles $D_n^+(z)$, represented as $D_n^+(z)$=$(z-z_1)(z-z_2).....(z-z_n)$.

Predictor filter is also represented as same as nominal plant
$F_r(z)$=$\frac{N_r(z)}{D_r(z)}$. and
Nominal plant model is
$G_n(z)$=$\frac{N_n(z)}{D_n(z)}$. so that $P_n(z)$=$\frac{N_n(z)}{D_n(z)}z^{-d_n}$.

In the designing of predictor filter it is necessary that $F_r(1)$=1, because it is a filter shall not influence the behavior of the system in steady state. So in the designing of predictor filter, first is find the $N_r(z)$ in such a way that
1-$z^{-d_n}F_r(z)$=$\frac{D_r(z)-z^{-d_n}N_r(z)}{D_r(z)}$=$\frac{(z-z_0)(z-z_1)(z-z_2).....(z-z_n)p(z)}{D_r(z)z^{-d_n}}$

In the above expression, last one has been obtained multiplying numerator and denominator by z^{-d_n}, p(z) is unknown polynomial and z_0=1.$D_r(z)$ is arbitrary defined, $N_r(z)$ all or some roots calculated so that it satisfy above expression identity, S(z) must be stable and given by below expression and (z-z_0)=(z-1) ensure that $F_r(1)$=1.

S(z)=$\frac{N_n(z)p(z)(z-z_0)}{D_n^-(z)D_r(z)}$

A simple tuning is consider that predictor filter is having multiple roots at z=β, where β is tuning parameter and vary 0 to 1. In many application,starting point of β is =$e^{\frac{-1}{d_n}}$ used. Finally $F_r(1)$ can be more roots than zeroes so that it attenuate measurement noise.

4.4 Experimental Setup and Result

In this section, used two PC for experiment.One PC is used as a controller and another one as a plant. These two PC are connected through the network. Controller is used here is FSP, which is having primary controller, nominal model of plant, time-delay(integrator time-delay) and predictor filter. Plant is having DC motor model transfer function which is obtain it previous chapter.The fig4.3 shown below represent the networked FSP with plant. In this fig4.3 PC-1 is controller part and PC-2 is plant part which is

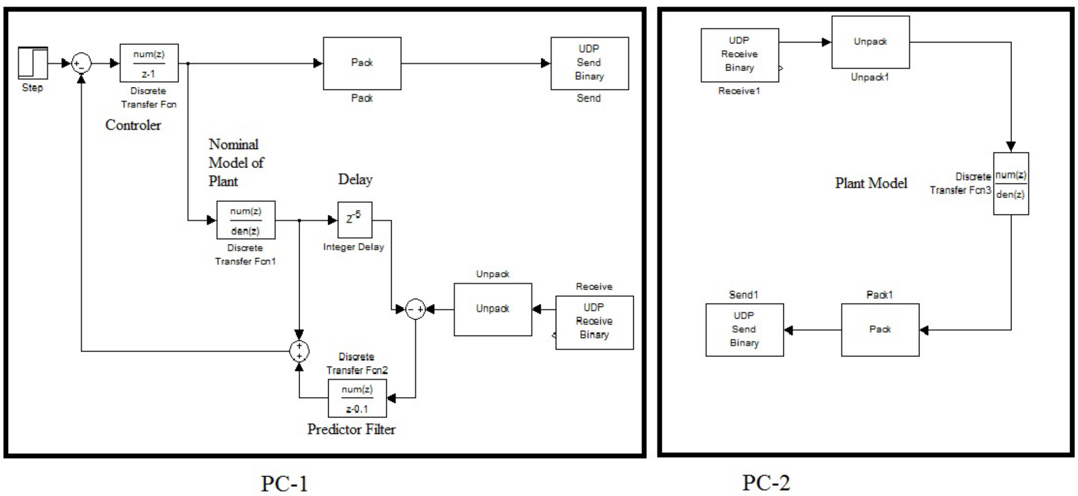

Figure 4.3: Networked FSP

controlled by FSP. Controller is FSP. FSP has primary controller, nominal model of plant, time delay and predictor filter. PC-2 is having plant, our case plant is consider DC motor model transfer function which is obtain from previous chapter represented as is continuous form

$$G(s) = \frac{71050}{5.18s^2 + 8180s + 10200}. \tag{4.1}$$

Now this is convert to discrete form with sampling period of 0.001 second. So that is become $G_n(z)$ which is also the nominal model of the plant which is delay free and is represented as

$$G_n(z) = \frac{0.0043z + 0.0025}{z^2 + 1.205z + 0.2062} \tag{4.2}$$

Plant is represented as Discrete state space model so that Convert this above equation into state space, we are getting A,B,C and D matrices as follow

A= $\begin{pmatrix} 1.0250 & -0.2062 \\ 1 & 0 \end{pmatrix}$ $B = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ $C = \begin{pmatrix} 0.0043 & 0.0025 \end{pmatrix}$

and D=0. Put these values in simulink model of the plant as discrete state space.Now we are calculating the value of $G_c(z)$.In previous chapter our plant is same so we apply same control scheme i.e. PI controller, using Ziegler-Nicholas tuning and obtain the values of K_p and K_i. Finally got the value of PI controller is given by

$$G(s) = \frac{0.1s + 13.88}{s} \tag{4.3}$$

Then it is converted to discrete domain and we obtain the value of

$$G_c(z) = \frac{0.1z - 0.08612}{z - 1} \tag{4.4}$$

Now the delay value is calculated, which is same as average delay value between the two PC. Average delay value between two PC is calculated in chapter-1, which is given by 1ms. So in the simulink block of controller, delay is also calculated. Now the final block is predictor filter. In predictor filter design, First we see in nominal model of the plant how many un desired poles, in our example all poles are desired. So that filter order is first hence first order transfer function is given by

$$F_r(z) = \frac{(1-\beta)(z-\alpha)}{(1-\alpha)(z-\beta)} \tag{4.5}$$

In our case α=0 because no undesired pole and β is tuning parameter. Its values varies from 0 to 1. Here we consider β=0.9 for good result. So that predictor filter is represented as

$$F_r(z) = \frac{0.1z}{z - 0.9} \tag{4.6}$$

Now the designing of discrete Filtered smith predictor is complete. As we

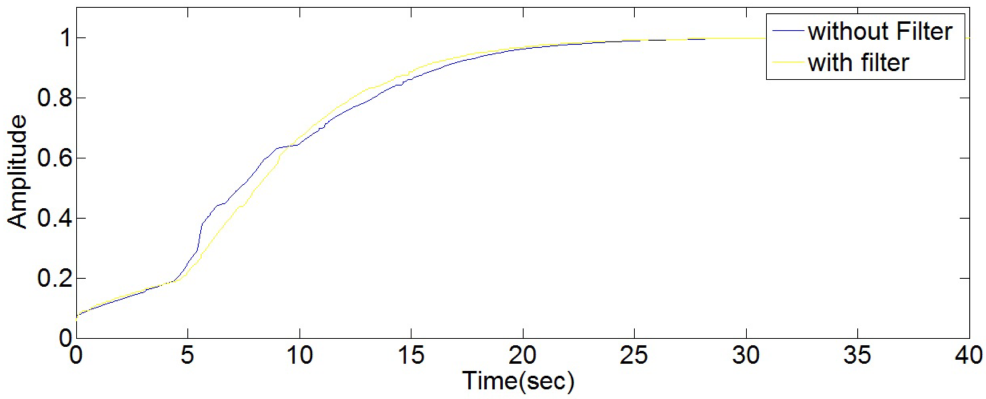

Figure 4.4: Result comparison with filter and without filter

see in the fig4.4 predictor filter attenuate the noise and smooth the output. It also reject the disturbance. In the above fig4.4 yellow is output with predictor filter and blue is the output with out filter. Both the output is same because there is no disturbance introduce but with filter graph smooth the gives slightly faster response.

4.5 Chapter Summary

In this chapter, we designed a discrete smith predictor which is compensate the delay and also designed a predictor filter which is used to reduce the noise introduce by the network as well as distortion. Discrete Smith predictor as well as predictor gives the good result.

Chapter 5

Design of a Discrete Low Pass Filter(LPF) & Analysis of Networked Smith Predictor Filter(SPF)

5.1 Introduction

The main goal of this chapter is to show how the filter study and design, understand the limitation of design. The filter designed by well known windowing technique.In window technique, first created the desired frequency response H(F), in the frequency domain then find its inverse frequency response(IFT). This is also a impulse response function H(k), after that discredited the impulse response function H(k) then truncated and windowed to form h_k in the time domain or spatial domain k. Notice that in the following discussion both H(k) and H(F) are in concinnous domain functions, where as h_k and h_F are their respective discrete forms. The truncation and windowing of h_k represents the Finite Impulse Response(FIR) digital filter, h_k.

The Impulse Response Function H(F) domain is infinite in principal, but it is truncated to some reasonable length to use in digital domain. The truncated form is h_k, Fast Fourier Transform(FFT) performed on it so that ringing is observed on the frequency response h_F in frequency domain. Moreover, the impulse response function h_k truncation distort the ideal filter characteristics in the frequency domain. So that truncation of h_k with its minimum effect in frequency domain, it is convolved with window function W_k, which do not distort the ideal filter characteristics and smoothly tapers the end in time domain. It is good for differentiate filter order and filter length. The filter is the highest power in z-transform of FIR filter and filter length is always one greater than filter order. If filter order is L that its length (L+1). Sometime filter order L is assume marginally greater than the Design filter order L_d.

5.2 Low pass filter design

Low pass filter design has following steps-

5.2.1 Impulse Response Function

The inverse fourier transform of desired unit step function H(F) is the continuous impulse response function $H_{LP}(k)$ for ideal low pass filter.

$$H_{LP}(k) = \frac{sin(\Pi.F_c.k)}{\Pi.k} \qquad -\infty < k < \infty \tag{5.1}$$

Then this is discredited to

$$H_{LP}(F_c) = \frac{Ksin(\Pi.F_c(\frac{N}{2} - k + 1)}{\Pi(\frac{N}{2} - k + 1)} \qquad k = 1, 2, ..., N + 1 \tag{5.2}$$

where F_c=$\frac{f_c}{f_N}$ is the normalized frequency, where f_c is the low pass filter cut off frequency and f_N is the Nyquist frequency($f_s/2$), where f_s is the sampling frequency,N is large number and K is gain factor.

5.2.2 Window Function

Several window function are available in signal processing like Kaiser, Blackmail, Harris-Nutgall and Gaussian etc. Some of them are good in rejection band attenuation properties and some of them are used in special cases.Gausian window has special properties that it can not change under fourier transformation. More it has simple calculation as well as performance is also good. So that use Gaussian window function and its discrete form is given by-

$$W_k = exp\frac{1}{2}[\frac{2\alpha}{L_D}(\frac{L}{2} - k + 1)]^2 \qquad k = 1, 2.......L + 1 \tag{5.3}$$

where L_D is the design filter order and α determine the full width at half maximum of the function. L_D is given by-

$$L_D = ROUND[(1+\varepsilon)(1+l)] \tag{5.4}$$

where ROUND(X) means only taken the integer part of X and ε is the fudge factor it vary from -0.5 to 0.5, ε=0 means design length and filter length are identical, ε¡0 means design length is smaller than final filter length and ε¿0 means design length is greater than final filter length.

Now this window function W_k is multiplied by the discredited impulse response function H_k.This multiplication gives the desired digital filter h_k, which is also called the filter coefficients.Hence The truncated and window function is found from

$$h_k = W_k H_k \qquad k = 1, 2, ...L + 1 \tag{5.5}$$

Now filter implementation, it has two ways first one is the direct or time domain and second is frequency domain implementation.The implementation is chosen according to the application.Here we used direct method or time domain method because filter length L is very small and this method is also used in real time application.

In direct method, we used concurrent processing in it filter gives values at the same rate at which input data is clocked in.In this process, first shift the data value by one position so that in $(L+1)^{th}$ position new data arrive and 1^{th} position data discarded then this data is multiplied by window function with current position data and sum this data gives the filter output.

5.3 Delay characteristics with the use of LPF

As shown in fig5.1 where α is constant and F_c is vary 0 to 0.6 then delay is reduce as increase in F_c. In fig5.2 where F_c is constant and α is vary 0 to 4 then delay is increase and in fig5.3 both α and F_c are varying in nature then this is a 3-d plot and see the delay variation.

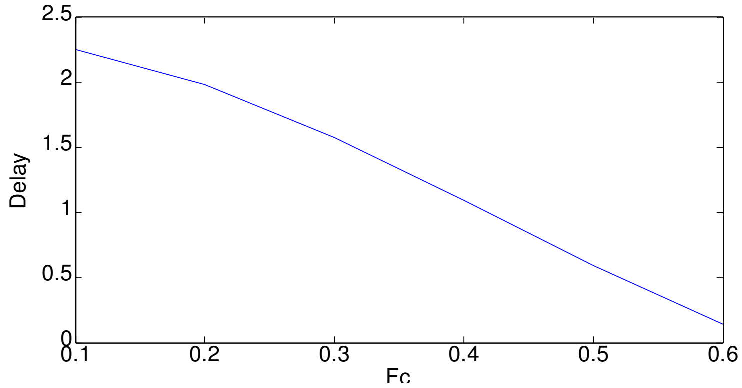

Figure 5.1: Effect On Delay With The Use Of LPF constant alpha

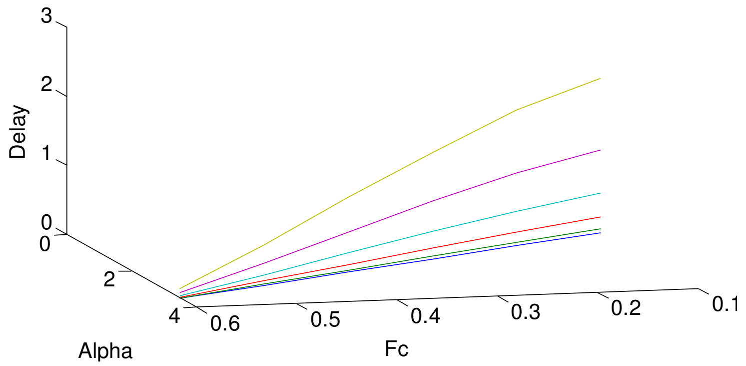

Figure 5.2: Effect On Delay With The Use Of LPF constant Fc

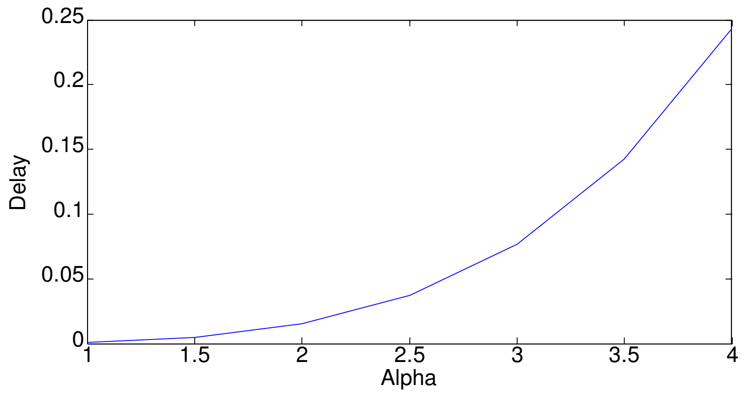

Figure 5.3: Effect On Delay With The Use Of LPF

5.4 Introduction of Networked Smith Predictor Filter

Here in this chapter, we compare the result of different combination of filter and Smith Predictor or we can say that with Smith Predictor and filter, without Smith Predictor and filter. The fig5.4 shows the block diagram of networked filter smith predictor.

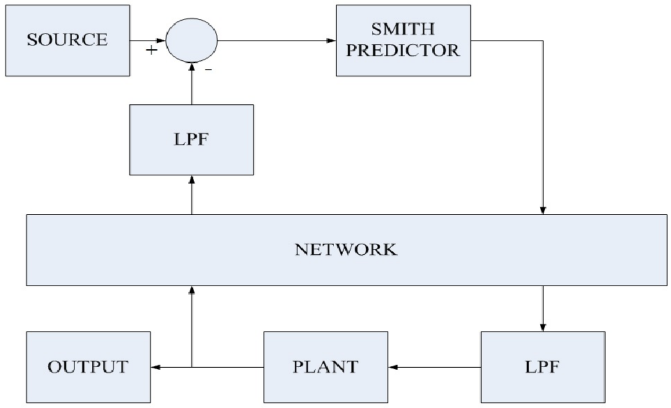

Figure 5.4: Networked Smith Predictor Filter

5.4.1 Smith predictor

Smith predictor is a type of predictive controller for systems with pure time delay, as in our case network is introduces time delay. Smith Predictor uses the mathematical model of the plant in the minor feedback loop. Advantage of this is that smith predictor technique for SISO system is directly applied to the MIMO system with same delay. Smith Predictor as shown in fig5.5.

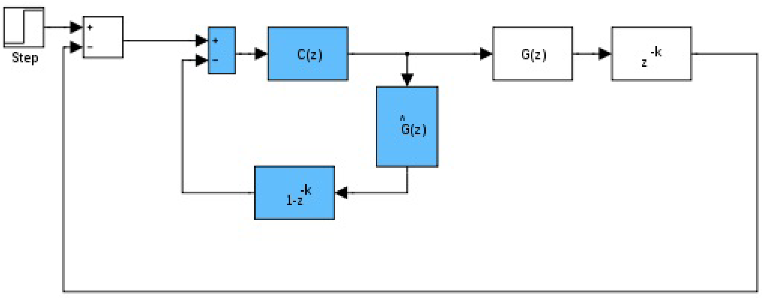

Figure 5.5: Smith Predictor

Suppose the plant consist of G(z) followed by a pure time delay z^{-k}.As a first step, we suppose only plant G(z), there is no delay associated with it and design a controller C(z) with close loop transfer function H(z)=$\frac{C(z)G(z)}{1+C(z)G(z)}$ that we consider satisfactory.

Now our next objective is to design a controller C1(z) for the plant G(z)z^{-k}(this time we consider the delay), such that close loop transfer function H1(z) equals to H(z)z^{-k}.

$$H1(z) = \frac{C1(z)G(z)z^{-k}}{1 + C1(z)G(z)z^{-k}} \tag{5.6}$$

and

$$H(z) = \frac{C(z)G(z)}{1 + C(z)G(z)} \tag{5.7}$$

both are equal so that

$$\frac{C1(z)G(z)z^{-k}}{1 + C1(z)G(z)z^{-k}} = \frac{C(z)G(z)}{1 + C(z)G(z)} \tag{5.8}$$

So that find C1(z) equals to

$$C1(z) = \frac{C(z)}{(1 + C(z)G(z))(1 - z^{-k}} \tag{5.9}$$

The controller C1(z) is used plant model and delay these combination is called smith predictor.

5.4.2 Plant, P-I controller and Low pass filter

Plant model is taken as a stable plant and it is given by-

$$G(s) = \frac{10}{5s^2 + 60s + 100} \tag{5.10}$$

Now P-I controller has been designed by the PID Ziegler-Nicholas tuning, which is explain in chapter-3, hence no need to explain again.finally P-I controller value is given by-

$$G(s) = \frac{K_p s + K_i}{s} \tag{5.11}$$

where K_p=8.28 and K_i=24.29

Filter is designed as first order Low Pass Filter it is given by-

$$= \frac{K}{1 + s\tau} \tag{5.12}$$

where K is the gain and τ is the time constant of the Low Pass Filter.Cut-off frequency of Low Pass Filter is given by- $f_c = \frac{1}{2\Pi\tau}$

Here we have taken low pass transfer function= $\frac{200}{s+200}$ and cut off frequency is// f_c=32 hz.

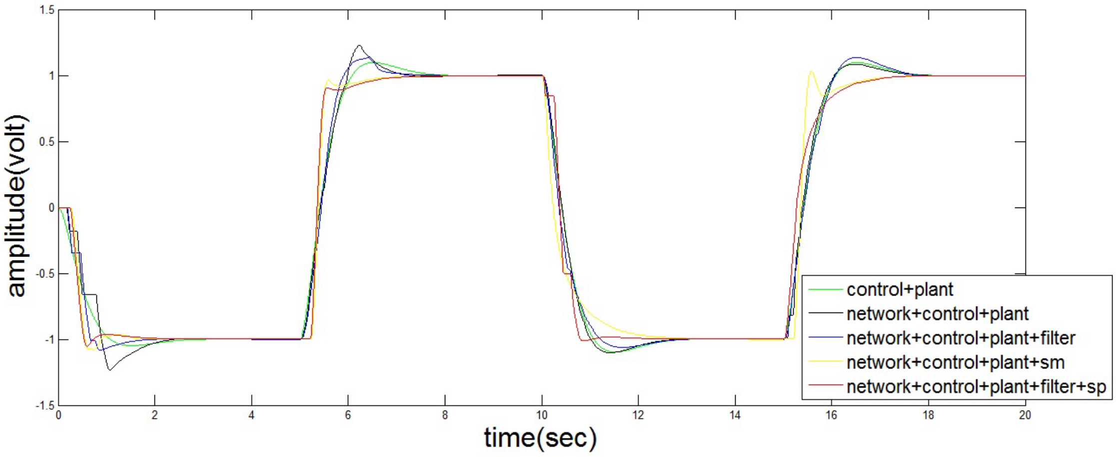

Figure 5.6: Different Configuration Results

5.5 Comparison of results for different combinations of LPF,SP and P-I controller

In above fig5.6 we see that green color line shows that with in one computer there is plant and controller so that there is no network or we can say that no delay. Then in black result shows that controller and plant are taken in different computer so that network is introduce or we can say that delay is introduce and noise is also present in it hence overshoot value is increased. Now low pass filter is considered so that it attenuates the noise which is shown in blue color result. Now in the next result instead of low pass filter, use smith predictor which gives the result in yellow color. Now finally red color result shows that use of network, low pass filter and smith predictor. In vertical transition where horizontal value is received then there is a packet loss in the information.

5.6 Chapter Summary

In this chapter seen the effects of the filter on delayed system. LPF design with window is not complex and here we use time domain implementation of LPF with con-current process.Here also designed Smith Predictor and filter for stable plant. Smith Predictor compensate the result and filter attenuate the noise.

Chapter 6

Conclusion and future work

NCS are distributed control systems that uses electronic networks in feedback loop. Use of such networks induces delay and packet loss in the closed loop.This thesis deals with development of a real-time networked DC servo system using MATLAB-Simulink for understanding the concept of NCS.PI controller and Smith predictor are implemented for the NCS.

6.1 Contributions of the Thesis

The following are the salient contributions of the thesis-

- The packet dropouts and delay in NCS occurs during data transmission from one network component to the other.
- A real-time networked servo platform for studying NCS characteristics is developed. This uses Matlab software, PCI 6221 as DAQ card as a connector cable between PC and PCI 6221 with the driver software.
- PID controller using Z-N tuning is performed and implemented in real-time for servo system speed control.
- Filtered Smith predictor used for delay compensation in the feedback loop and design predictor filter.

6.2 Future work

- Controller used here are not adaptive to match with the stochastic behavior of network characteristics, an adaptive or predictive controller implementation may be the next work.
- The networked servo control system developed here is connected to a LAN. This may be extended to, Internet based servo control system.

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